ET Docket No. 98-80

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Office of the Secretary
Federal Communications Commission
P.O. Box 678
Washington, DC 20554

In Regards to: FCC Notice of Inquiry, 1998 Biennial Review - Conducted Emissions Limits Below 30 MHz for Equipment Regulated Under Parts 15 and 18 of the Commission's Rules, released June 8, 1998

To Whom It May Concern:

The attached report specifically addresses the following question posed in the reference NOI:

"Is there an alternative, more preferable means to control interference to services operating below 30 MHz caused by radio frequency devices and ISM equipment? If so, what alternative approach is appropriate?"

The attached report introduces, explains and justifies a new conducted emission limit and measurement technique based on conduction mode isolation (separate limits for differential and common mode emissions). As explained in the report, conduction mode isolation is a well-established technique used in rf filter design. The report explains why an extension of this technique to regulatory matters is desirable.

I can be contacted during work hours at:

phone 256/971-9527, fax: 256/971-9475, e-mail: javork@hsv.sverdrup.com

Sincerely,

Ken Javor

Ken Javor

Attachment: Report: Investigation Into Radio Susceptibility To Power-Line Conducted Noise

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INVESTIGATION INTO RADIO SUSCEPTIBILITY TO POWER-LINE CONDUCTED NOISE

KEN JAVOR

EMC COMPLIANCE

HUNTSVILLE, ALABAMA

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INVESTIGATION INTO RADIO SUSCEPTIBILITY TO POWER-LINE CONDUCTED NOISE

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ABSTRACT

Radio receiver response to power-line conducted noise is studied. Over thirty radios are evaluated as to their susceptibility to common and differential mode noise. Such evaluation, to the author's knowledge, is novel. Results are compared to more conventional susceptibility evaluation techniques.

Study results show radios are much more susceptible to common mode (cm) noise (that which is a common potential on all power wires relative to power reference) than to differential mode (dm) noise (that which is developed between phase and neutral). Statistically significant differences between these responses suggest the efficacy of conducted emission (CE) procedures and limits which separately control cm and dm CE. This report is organized into four parts. It opens with a background discussion of traditional CE control, sources of CE, and methods for separating conduction modes. Rationale for expecting different radio sensitivity to cm/dm CE is presented. The next section describes a well-controlled test to measure the effect. The third section describes test results, including response of different radio models and types, and individual radios at different tuned frequencies and different received signal-to-noise ratios. The last section discusses effects on filter design for an OEM type off-line switched mode power supply (SMPS) used in a personal computer. Filter design to meet present day CE limits is shown to be more difficult and expensive than that required to simply protect radio receiver victims.

Study conclusion is that adoption of new standards which reflect real radio frequency interference will decrease cost of EMC compliance, with benefits resulting to the entire electronics marketplace.

1. BACKGROUND

Commercial conducted EMI standards imposed by governmental authority as a requirement for entry into the marketplace protect radio receivers from the effect of power-line rfi. This is why CE control is exerted in the frequency domain: test frequency range, bandwidth, and quasi-peak detection all are tailored to protect reception of amplitude modulated radio signals.

1.1 CE CONTROL PROCEDURES

Necessarily, conducted noise is measured and controlled between power conductor and ground. But the meaning of power conductor has changed over time. At the genesis of rfi control, power conductor meant phase or feeder, while ground meant both current return and power system reference. Hence genesis and evolution of today's line impedance stabilization network (LISN), whose topology and circuit performance is specified as line-to-ground. Early standards inserted a LISN between power conductor and return, with return being power source reference. (Figure 1, left). Determination of AM radio susceptibility to power-line CE (in order to set CE limits on office and information technology equipment) was made using this topology. (CBEMA, 1977) Today, power conductor is any power current carrying conductor, which includes neutral. Today's test inserts a LISN in each current-carrying conductor, each LISN bonded to power source reference (Figure 1, right). With this definition and configuration, conducted emissions appear not only between power conductor and ground, but also between different power conductors. Commercial CE standards, in accordance with tradition, control rfi measured between each current carrying conductor and ground (power system reference).

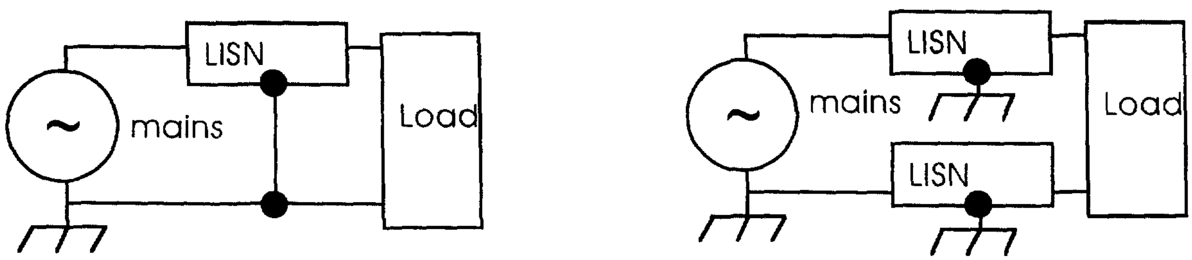


Figure 1: *LISN placement and grounding, early and present, left to right*

1.2 PHYSICAL SOURCES OF CE

Regardless of measurement technique, there are two mechanisms for generating CE in the off-line load. One is a time varying impedance between phase and neutral, resulting in a time varying current draw. This line-to-line mode (l-l) is sometimes designated transmission line or normal mode, since CE current flows in the same path as power current, i.e., in the power transmission lines. Differential mode (dm) is the most familiar designation for this type of CE. Switching action of an SMPS, drawing switched current from the power bus, as shown in Figure 2, is an example. Current drawn from phase conductor passes through the time varying impedance (transistor junction) and returns to power source on the neutral conductor. The second mechanism is a time varying voltage driving current into chassis through a parasitic capacitance. An example of this mode is rectified line voltage (170 Vdc) on the case of the same switching transistor, with said transistor mounted to chassis for heat dissipation purposes, as shown in Figure 3. Electrically insulating material is interposed between transistor and chassis. A low value capacitor is formed. Current due to the $C\frac{dV}{dt}$ product is driven into chassis. Under normal conditions, rfi potentials measured at each LISN EMI port due to the line-to-ground source are very nearly equal, that is common; hence this noise mode is often termed common mode (cm).

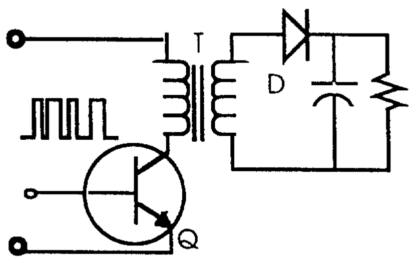


Figure 2: *Source of line-to-line CE*

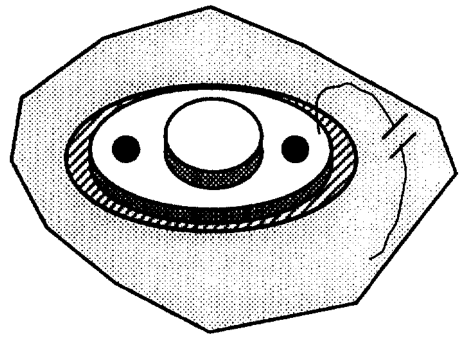


Figure 3: *Source of line-to-ground CE*

Current flow in a two conductor above ground configuration (that used for CE measurements) is shown for each mode in Figures 4 and 5. In these figures, physical sources of CE are modeled as simple voltage sources, and the power source is represented only by its line impedance simulation, which is 50 Ω to ground in the AM band.

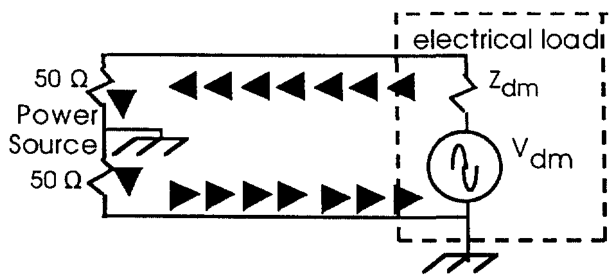


Figure 4: *DM CE current flow*

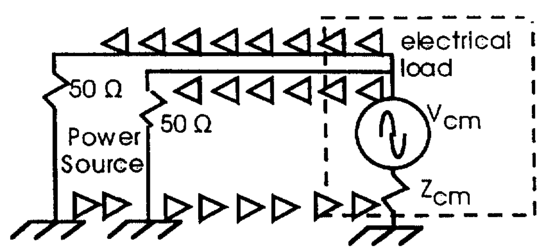


Figure 5: *CM CE current flow*

1.3 MEASUREMENT OF CE

Figure 6 diagrams total rfi potentials on each power conductor when all sources of CE are taken into account. Note that total rfi potentials measured at phase and neutral LISN ports will be vector sums and differences of cm and dm CE, respectively.

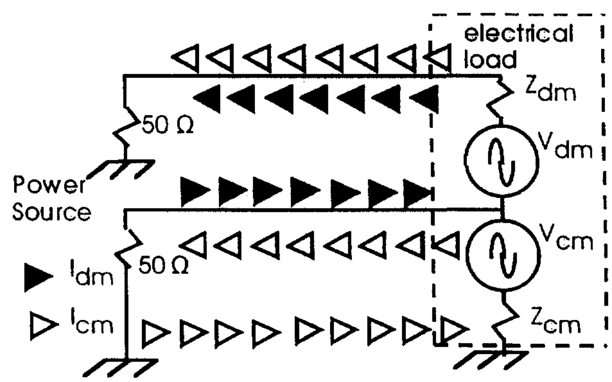


Figure 6: *Composite cm/dm current flow in two conductor above ground power bus*

Figure 7 illustrates that, in contrast, an emission generating test sample connected to a single LISN inserted between phase and neutral can only generate an emission potential between that same phase and neutral. It has but one CE degree of freedom, even though two separate noise sources still exist. (Single LISN case is shown here for reasons which will become apparent when discussing radio receiver susceptibility to conducted rfi.) Figure 6 is the case in modern practice, with a LISN connected between each current carrying power conductor and power system reference. Two CE noise potentials are possible, line-to-ground, and line-to-line; two CE degrees of freedom.

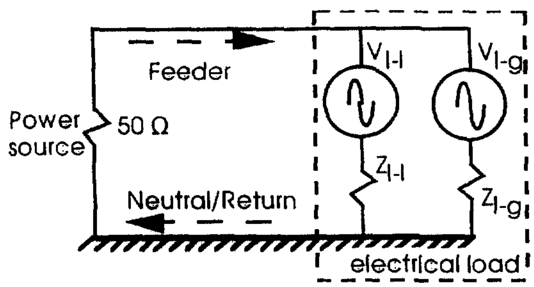


Figure 7: *RFI noise sources & resultant current flow with single power conductor above ground*

Topetto (1979), Nave (1986) and Paul (1988) realized that filter design to meet CE limits is optimized by designing to separately control each emission mode. MIL-HDBK-241, Design Guide for EMI Reduction in Power Supplies, discussed sources and containment of conducted emissions in the early 1980s. Since compliance measurement techniques do not provide mode specific CE data, attempts were made to invent circuits which can provide this information. Nave (1989) invented a very successful differential mode rejection network (DMRN) and marketed it under the trade name LISNMATE. A companion common mode rejection network (CMRN), trade named LISNMARK, is also available commercially. Each of these networks attenuates the unwanted mode by 50 dB over CE measurement frequency range. Effectiveness and utility of these networks was documented by the author in several cases (Javor 1994, 1995, course notes). These articles, and Nave (1986) explain different sources of cm and dm CE, as well as different filter techniques and constraints which must be employed and obeyed. Following two observations are noted:

1) Measured CE are a linear combination of two independent kinds of CE, line-to-ground, or common mode, and line-to-line, or differential mode.

2) Commercial radio receivers are provided only phase/neutral (no safety ground) power wiring, disabling any technique providing line-to-ground filter protection.

While present CE standards and test methods are *sufficient* to provide EMC in most cases, the above two observations led the author to question whether present standards and test methods are *completely necessary* to provide for EMC, or whether it might be important to consider radio CE susceptibility by modes when specifying control of conducted emissions. Before addressing this issue further, it is necessary to review the history of commercial CE control.

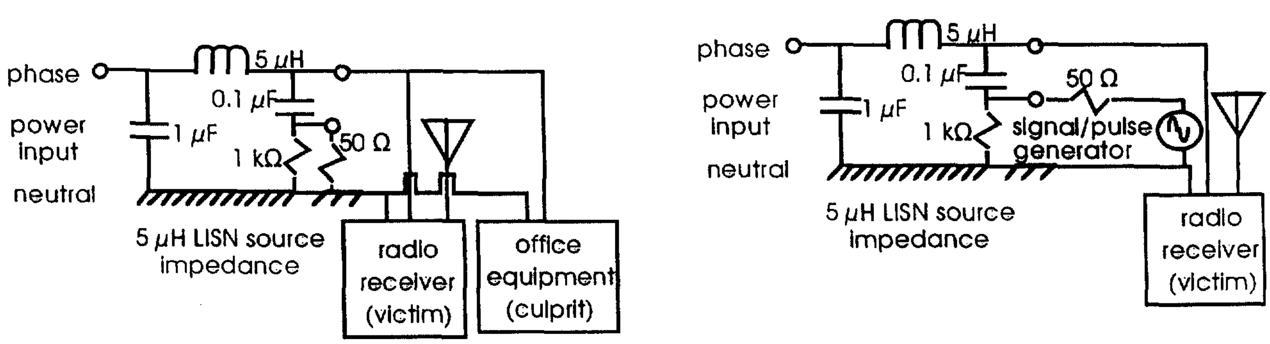
1.4 EARLY CE CONTROL

Rationale for control of CE prior to 1978 was based on radio and television receiver local oscillator emanations as well as induction cooking ranges operating in band to AM radio reception. These were the only sources of AM band rf energy, hence CE control was imposed only on these classes of power bus loads. Such control was exerted via use of two 5 µH LISNs, inserted in phase and neutral conductors, with ground reference. Frequency range extended from 300 kHz to 30 MHz (lower for induction cooking).

1.4.1 DETERMINATION OF AM RADIO SUSCEPTIBILITY TO POWER-LINE NOISE ARISING FROM ELECTRICAL SWITCHING (ADAPTED FROM JAVOR, 1993)

In the late 1970s, a new source of rfi appeared; office/information technology equipment which utilized electrical switching techniques. Fourier spectra of such switching extended into radio bands. An industry group, the Computer and Business Equipment Manufacturers' Association (CBEMA) initiated a program to quantify and recommend solutions. Results were documented in the CBEMA ESC5 report (CBEMA, 1977). Following is a summary of CBEMA investigation into CE control.

Victim receivers were powered through a common impedance with several culprit emitters (office/information technology equipment) and thresholds of interference were established. These thresholds of interference were massaged into limits. Figure 8 shows initially planned testing (part a) and actual testing (part b). Victims were a selection of AM radios bought at typical consumer outlets. Common source impedance chosen was the traditional 5 µH LISN. Culprits were initially office equipment, but it was realized that conducted emissions from office equipment were fixed in nature, making victim radio thresholds of interference difficult to determine. It having been previously established that some office equipment conducted emissions did cause radio interference, culprits were replaced by CW and pulse generators of 50 Ω source impedance driving adjustable signal levels into the LISN port. Thresholds of interference thus determined were the basis for FCC limits.



a) Original set-up to determine susceptibility of radio receivers to office equipment CE

b)Actual set-up used to determine susceptibility of radio receivers to CW and pulsed CE

Figure 8: *Limit Determination for office equipment CE*

In contrast to the technique used to measure TOI, CBEMA recommended CE measurement technique follows that of the earlier part 18 CE test set-up. The CBEMA report recommends a compliance technique utilizing a 50 μH, 50 Ω LISN in each current carrying power conductor.[1] The report explicitly addresses the effect on radio TOI due to a second source of CE available when power bus configuration supplies an above ground neutral. The CBEMA report assumes that the conducted voltage at which TOI occurs would decrease 6 dB, due to twice the amount of CE available with this measurement technique.[2]

1.5 STUDY PURPOSE AND SCOPE

It is this last assumption which was studied and is challenged by the author in this report. The assumption appears reasonable as long as the second source of EMI is held to be identical to the first. Equation set 1 models the CBEMA assumption.

$$\text{TOI single LISN (dB}\mu\text{V)} \sim \text{Vmeasured} \qquad \text{Eqn. 1-1}$$

$$\text{TOI two LISN (dB}\mu\text{V)} \sim \frac{1}{2} \cdot \text{Vmeasured} \qquad \text{Eqn. 1-2}$$

As we have seen, however, the two LISN test technique measures two different types of CE, cm and dm. What is measured at each LISN port is a linear combination of these two noise components. An accurate mathematical analogy is that cm and dm noise components are two basis sets which together span the space of measurable line-to-ground CE. Equation set 2 models author's assumption.[3]

$$\text{LISN 1 (dB}\mu\text{V)} \sim [V_{cm} + V_{dm}] \qquad \text{Eqn. 2-1}$$

$$\text{LISN 2 (dB}\mu\text{V)} \sim [V_{cm} - V_{dm}] \qquad \text{Eqn. 2-2}$$

$$\text{TOI author's model (dB}\mu\text{V)} \sim [\alpha V_{cm} + \beta V_{dm}] \qquad \text{Eqn. 2-3}$$

With the model of 2-3, the CBEMA assumption is only valid if $\alpha \approx \beta$. If this is not the case, as the author suspected, then it makes sense to control CE by modes, with the degree of strictness proportional to the ratio of α to β, that is cm to dm susceptibility.

The next section of this report explains issues involved in setting up a well-controlled test, and describes test set-up and procedures for empirically determining the $\frac{\alpha}{\beta}$ ratio. The third part shows test results, with statistical analysis of results by tuned frequency, signal-to-noise ratio, and across a broad range of radio receiver models and types. The last part demonstrates benefits resulting from CE control by modes.

---

[1] Use of the 50 μH LISN in lieu of the 5 μH LISN is in part due to the European practice of extending the AM broadcast band as low as 150 kHz. The 5 μH LISN provides a very low power stabilization impedance at 150 kHz (private communication with Mr. Edwin Bronaugh).

[2] CBEMA, 1977, ESC5 Report, paragraph 5.6.2, p. 5-24, 5-25

[3] There are conditions under which it appears as if another independent noise mode exists. This occurs when bulk storage capacitance does not adequately provide a common potential for both phase and neutral at the switching frequency. But it is only the action of an imperfect filter element which gives this appearance. It does not change the fundamental nature of the physical sources of CE, which are voltage sources driving rfi currents through parasitic capacity into chassis and time varying line-to-line impedances. (Nave, 1986)

2.0 CHARACTERIZATION OF RADIO SUSCEPTIBILITY TO CM AND DM CE

Test plan is to measure radio TOI under controlled conditions, with the only variation being noise mode injected into power line. Several parameters must be carefully controlled, in order to assure valid test results. Parameters requiring control and control implementation (Desiderata) are listed tabularly below. A schematic representation of test set-up designed to effect controlled conditions is shown in Figure 9.

2.1 DESIDERATA

CONTROLS NEEDED	HOW CONTROL WAS EXERTED
1. RADIO OPERATION RELATED	*RADIO RECEIVER OPERATION IS CONTROLLED BY*
a) definition of received broadcast signal level to radio noise floor ratio	a) simulating a broadcast station, (30% amplitude modulated @ 1 kHz) of sufficient amplitude to induce an audio response at 10 dB $\frac{S+N}{N}$ ratio. This is accepted technique for establishing AM radio sensitivity.[4] Rf signal is either radiated into test chamber, or directly injected into radio antenna port.
b) definition of rfi to broadcast signal level ratio (quantifiable definition of TOI)	b) TOI is defined to be LISN EMI port rf amplitude which causes an audio output response 6 dB below audio output due to simulated broadcast level
c) all radio control settings fixed for test (tuned frequency, volume control)	c) Once radio has been tuned to broadcast signal (from synthesized signal source), and volume has been adjusted to comfortable level, radio is not touched until test is over.
d) mixer below saturation	d) Radio is placed in shielded enclosure with approximately 60 dB of attenuation to AM broadcast ambient. Unmodulated test signals introduced into chamber at high enough levels to cause mixer non-linearities are shown to be 40 dB higher than AM ambient within enclosure.
e) IF amplifier below saturation, and free from adjacent signal leakage	e) Radio is placed in shielded enclosure with approximately 60 dB of attenuation to AM broadcast ambient. Testing showed that IF amplifier could be affected if an adjacent signal (within 20 kHz of tuned frequency) was 20 dB or more above simulated broadcast level. Shielded enclosure use precludes this condition at all frequencies after sundown.
f) post-detection stage automatic gain control at same level throughout test	f) This condition limited dynamic range of broadcast signals used when measuring TOI. Linearity of audio output increase with rf signal increase was carefully monitored.
g) radio fixed relative to microphone pick-up & "broadcast" antenna	g) Once radio has been tuned to broadcast signal (from synthesized signal source), and volume has been adjusted to comfortable level, radio is not touched until test is over.

[4]ARRL Handbook for Radio Amateurs, 72nd edition, 1995

CONTROLS NEEDED	HOW CONTROL WAS EXERTED
2. TOI DETERMINATION	*TOI DETERMINATION IS PERFORMED UNDER THE FOLLOWING CONDITIONS*
a) Rfi signal must simulate real world plus have constant amplitude, frequency, and modulation characteristics	a) Rfi signal is unmodulated, and offset in frequency from simulated broadcast signal is within radio's IF pass band. Rfi is a beat frequency effect. Rfi signal is offset from broadcast signal by 400 Hz.
b) constant frequency relationship between broadcast signal and rfi signal	b) Both rf sources are synthesized signal generators with frequency accuracy /stability of 10 Hz for rfi source and 1 Hz for simulated broadcast signal source in AM band.[5]
c) precise, measurable, repeatable technique for determination of audio output levels	c) Audio output is monitored via either an external microphone or directly from a radio microphone jack, when available. Audio signal is connected to a sound card in a PC, and a software generated audio spectrum analyzer is used to monitor radio audio output, in addition to listening. Audio response to both broadcast and rfi signal are clearly visible as separate signals above noise floor, and relative levels are measured, compared, and recorded.
d) is rfi effect through direct conduction or radiation from radio ac power cord?	d) When injecting rfi into a radio's ac power cord through a pair of LISNs, it is always possible that radiation of rfi from power cord is coupling into radio's antenna, and that susceptibility is via this mechanism, not directly through conduction. A separate, filtered source of ac power was available in shielded enclosure. Each radio was additionally tested in following mode. Radio was powered from filtered ac outlet, and a dummy three-wire power cord, terminated with 50 Ω from phase and neutral to green wire, was arranged in same manner as radio power cord when connected to LISNs. Rfi signal source amplitude was increased until radio TOI was achieved (when possible). Rfi level was compared to that which caused TOI in standard test. If alternate power source test rfi level was higher than during conducted test, this was taken as proof that effect was conducted. This was always the case. In many cases, maximum signal source amplitude was insufficient to cause TOI during alternate power source test.

[5]Rfi source is a Farnell PSG1000; simulated broadcast source is a Farnell PSG2400. These may be phase locked together for maximum stability, but this was found to be unnecessary for the purpose of this test.

CONTROLS NEEDED	HOW CONTROL WAS EXERTED
3. RFI CIRCUITRY RELATED	*INTERFERENCE GENERATION CIRCUITRY*
a) injection technique must have high rejection of unwanted mode; this determines dynamic range of measurement	Technique designed for this effort by Mr. Mark Nave of EMC Services, at author's request. Very similar to commercially available LISNMATE/ LISNMARK, but provides both modes with identical circuitry, the flip of a switch being only difference between modes. Figure 10 shows output with 1 Vrms input from 50 Ω signal source. A 3-port device, dubbed selectable mode injection network (SMIN) by author, provides 50 Ω termination to signal source and each LISN, and rejects undesired mode by at least 46 dB in AM band (below 1600 kHz). Figure 11 shows SMIN mode rejection.
b) constant rfi source impedance regardless of injection mode (cm/dm/line-to-ground)	b) SMIN provides 50 Ω termination at each of its three ports, regardless of switch position. Figure 10 shows SMIN cm and dm outputs into 50 Ω with identical input.
4. DESIRED INFORMATION IS:	*DESIRED INFORMATION WAS OBTAINED AS FOLLOWS:*
a) radio susceptibility to cm, dm, and line-to-ground rf noise w/minimum discernible signal	a) For each radio, a minimum of three configurations were tested. These were cm/dm injection into two 50 μH LISNs, and line-to-ground injection into a single 5 μH LISN, hereinafter referred to as CBEMA mode.
b) radio susceptibility to cm, dm, and line-to-ground rf noise with higher level signals	b&c) For any given test, broadcast level and frequency were held constant, but many radios were tested with several different broadcast levels, and at low, mid, and upper frequencies (relative to AM broadcast band).
c) radio susceptibility as a function of frequency	

(Following sections on procedures, set-up and configurations are selected detailed developments of Desiderata, and are annotated to show correspondence.)

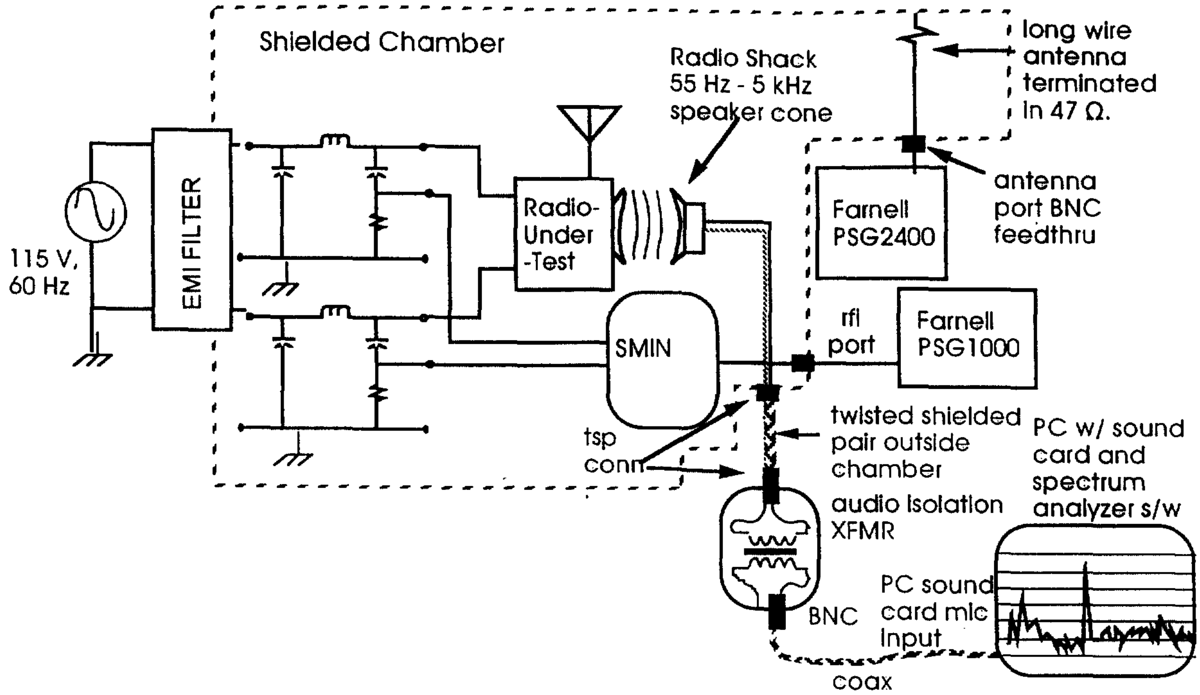


Figure 9: *Radio TOI determination test set-up*

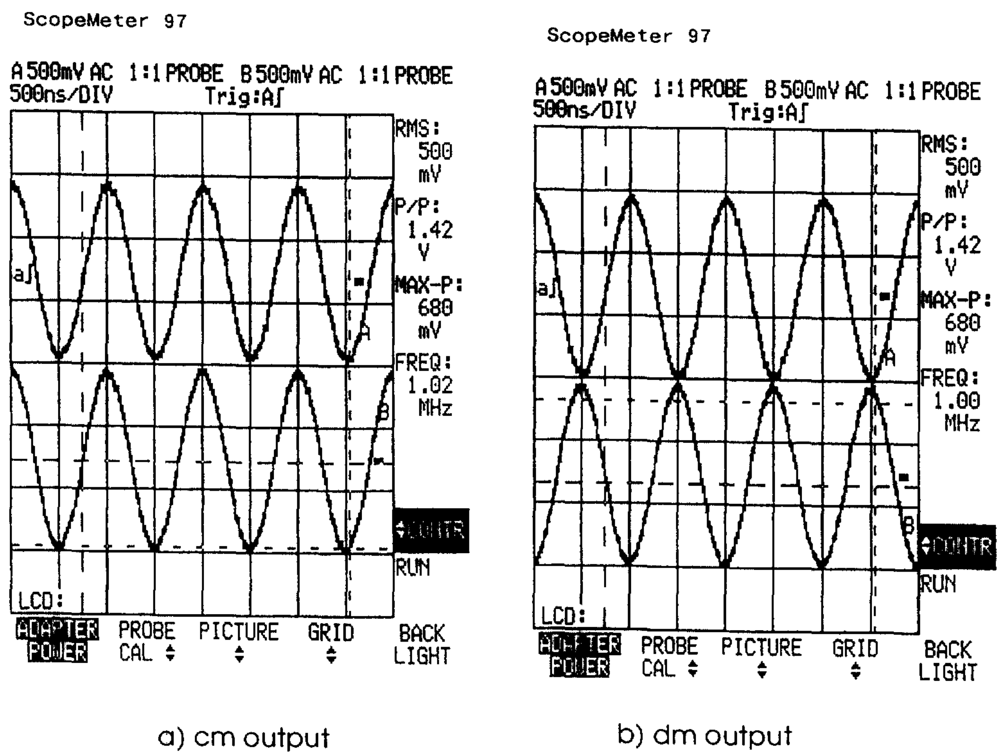


Figure 10: *SMIN output with 1 Vrms input from 50 Ω source*

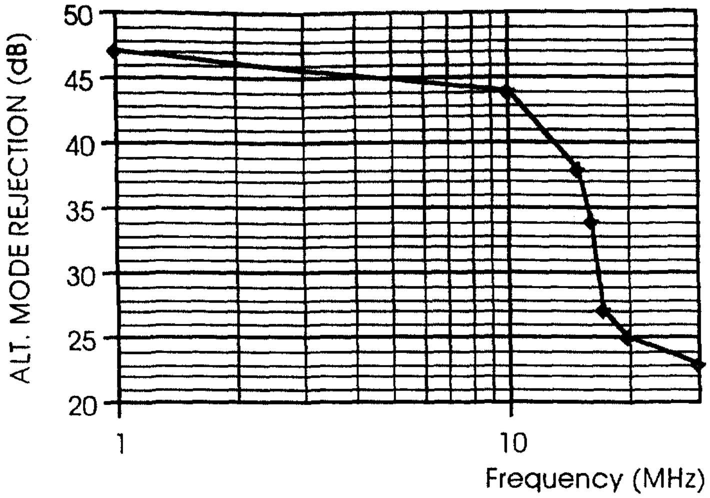


Figure 11: *SMIN alternate mode rejection*

2.2 DETAILED TEST PROCEDURE (annotated with respect to Desiderata table)

[1a,b,f, 2c] A sample test data sheet, with detailed instructions, is shown in Figure 12. One such test data sheet is used for each radio configuration tested. The audio spectrum analyzer (denoted PCSA on worksheet) was used to absolutely verify a given level of audio output. As stated earlier, intent is to generate a simulated broadcast signal yielding a 10 dB $\frac{S+N}{N}$ audio output from radio (see Figure 13). Actual ratio is not as important as precise repeatability of ratio for each test configuration. TOI point was somewhat arbitrarily defined to be 6 dB down from broadcast signal audio output (see Figure 14). Again, exact ratio (rfi vs. broadcast induced audio output) is not as important as maintaining a precise relationship between broadcast and rfi signal levels for each rfi mode and radio test configuration. Process of determining all these levels is as follows. Audio spectrum analyzer noise level in absence of broadcast signal is measured. Broadcast signal is increased until 10 dB $\frac{S+N}{N}$ is approximately reached. This level is recorded (both audio spectrum analyzer amplitude, and signal generator rf power that caused it). TOI level is then calculated to be 6 dB down from broadcast response audio amplitude. At this point rfi simulating signal generator rf output is enabled (with a particular injection mode selected), and increased in amplitude until TOI point is reached (rfi signal generator tuned to broadcast signal frequency plus 400 Hz). Rfi signal generator level is recorded. For enhanced repeatability, PC mouse controlled cross-hair is placed at rfi induced audio level prior to mode switching. After mode switching, signal generator output is then increased/decreased as necessary until rfi level is exactly that which it was before, after checking that simulated broadcast signal level has not changed. Rfi signal generator level for this injection mode is recorded.

2.2.1 PHYSICAL TEST SET-UP *(annotated with respect to Desiderata table)*

[1d,e] Figure 15 shows physical layout. Shielded enclosure is a modified 19" rack. Modified rack AM band attenuation of external ambient is about 60 dB. This is not sufficient to yield a pristine ambient at the EMCC test facility during daylight hours, but after sundown it provides usable performance. Shielding the test set-up allows TOI determination with simulated broadcast signals at a level producing a 10 dB $\frac{S+N}{N}$ audio output ratio, per established definition of AM band

radio sensitivity. Ambient signals within shielded enclosure were well below this level, allowing simulated broadcast signals to be at proper levels. Figure 16 a,b,c are ambients (antenna-induced potentials on long wire antenna) outside and inside enclosure, and level of simulated broadcast signals relative to enclosed ambient. In b) rf signal level causing 10 dB $\frac{S+N}{N}$ radio response is highlighted. In c), radio receiver IF leakage is visible 455 kHz above tuned frequency.

[1g, 3b] Radios are supported on a wooden shelf well above ground plane, in a manner similar to that of ANSI C63.4. However, separation is not a full 80 cm. Furthermore, enclosure sides and top are much closer to radio than 80 cm. This is not deemed critical to test integrity. Whatever the stray capacity from radio end of power cord to enclosure, it is fixed for any given radio-under-test configuration (radio nor power cord wrapped on serpentine cable fixture is moved during entire suite of tests[6]). Also, reactive impedance of this stray capacity (in AM band) is so high with respect to 50 Ω source impedance of rfi generator as to be virtually open circuit, regardless. The only change between a cm and dm measurement is SMIN switch position and attenuator setting on PSG 1000 rfi signal source.[7]

[2d] Figure 17 shows the alternate power source technique for verifying that induced susceptibilities are indeed of a conducted, rather than radiated nature. After making measurements per Figure 15, radio is plugged into an alternate source of filtered ac power. A two-wire (black/white) power cord of similar length to radio's is connected to LISN and serpentine wrapped. This power cord is terminated line-to-line with a 1μF capacitor in series with 50 Ω. With both injection modes, PSG 1000 rfi generator output is set at levels which either duplicate previous results (audio interference relative to broadcast signal) or are well in excess but have not induced previous rfi levels.

[4a] Figure 18 shows this study's version of original CBEMA technique. Radio/power cord are unmoved from mode isolated set-up. In this set-up the 5 μH LISN returns current on its chassis; it must be isolated from enclosure or 60 Hz ground loop currents pollute audio signal at PC. Similarly, a low frequency block was placed between rfi signal source and LISN EMI port. This consisted of breaking the coaxial shield and installing 1 μF in series. An external 20 dB pad was connected between rfi source and LISN, which allowed safer operation, and was identical to the 50 μH LISN, which had built-in 20 dB pads.

2.3 TEST CONFIGURATIONS (annotated with respect to Desiderata table)

[4a,b,c] Each radio is subjected to three tests described above: TOI measured in terms of dBμV at LISN end of power cord for pure cm, dm, and line-to-ground injection. Other tests are performed to rule out contributions from uncontrolled variables. Although most radios are tested near a mid-band frequency of 1 MHz, not all are so tested, and a question of response as a function of frequency might be raised. Seven radios have cm vs. dm TOI ratios tested at low-, mid- and high-band frequencies. Purpose here is to show variations vs. frequency small relative

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[6]Serpentine cable fixture was installed near radio, not LISN. This was for convenience, but not in accordance with standard procedures which require placement near LISN end of cord. For this study, standard placement was not deemed critical.

[7]Line-to-ground impedance is 50 Ω for all test modes. Unavoidably, given a two LISN test set-up, dm rfi source impedance line-to-line is 100 Ω (AM band); whereas cm source impedance (taking both lines into account) is 25 Ω. Simply an artifact of C63.4 test configuration, which is taken into account during filter design.

to actual TOI differences, ruling out tuned frequency as a contributing variable. Another possible source of error is linearity of TOI determination vs. simulated broadcast level. Different radios (with vastly different sensitivities) require different broadcast levels to yield a standard audio output (10 dB $\frac{S+N}{N}$). When comparing TOI of different radios, normalization must be introduced. Is normalization valid? In order to answer this question, several radios are measured for cm vs. dm TOI ratios as a function of output signal to noise ratio (10 - 60 dB in 10 dB steps). This means that in each successive test for a given radio, simulated broadcast level is increased 10 dB. Near constant cm vs. dm TOI ratios over this large dynamic range rule out variability due to different radio sensitivity.

DATE:__________
SPECIAL NOTES:

WORK AND DATA SHEET

Radio-Under-Test (UUT) Identification:____________________.

1a.	Tune (uut) to clear channel, default 1 MHz.	Record test frequency: _____.
1b.	Place pickup spkr on uut spkr or in fixed relative position.	
2.	Connect PSG2400 to chamber antenna port. PSG2400 w/ 30% AM @ 1 kHz. Precisely tune uut to PSG 2400 frequency. Reduce PSG2400 out-put until 1 kHz signal w/ 10 dB S/N ratio is achieved. Record level with mouse controlled cursor at peak.	Record spectrum analyzer 10 dB S+N/N level:_____, and PSG2400 output that causes it:________.
3.	Ensure spectrum analyzer frequency axis displays dc to at least 3 kHz.	
4.	Connect PSG1000 to rfi port, PSG1000 @ PSG2400 freq.+ 400 Hz, cw.	
5.	Note which mode is selected.	Mode: _____.
6.	Increase/decrease PSG1000 setting until 400Hz beat frequency amplitude is 6 dB below 1 kHz level (i.e., 4 dB S+N/N). Ensure compression of 1 kHz level due to AGC is accounted for. Maintain 4 dB ratio between compressed 1 kHz and 400 Hz rfi levels. Record (place mouse controlled cursor on peak amplitude) PSG1000 amplitude display as threshold of interference (TOI) for that mode. Record PSG1000 level (dBμV).	Record PSG1000 output (dBμV) (TOS) using that mode______. _____ dB @ 400 Hz on PCSA.
7.	Switch to other mode.	Record mode: _____.
8.	Increase/decrease PSG1000 level until 400 Hz signal level is same as that achieved in step 7. Record PSG1000 level (dBμV).	Record new TOS (dBμV):________.
9.	The difference in the Step 7 and step 9 TOS (dB) is the difference between cm and dm susceptibility.	Record Step 7 - Step 9 result:______. Note whether uut is more sensitive to cm or dm interference: ____.

Figure 12: *Work and data sheet*

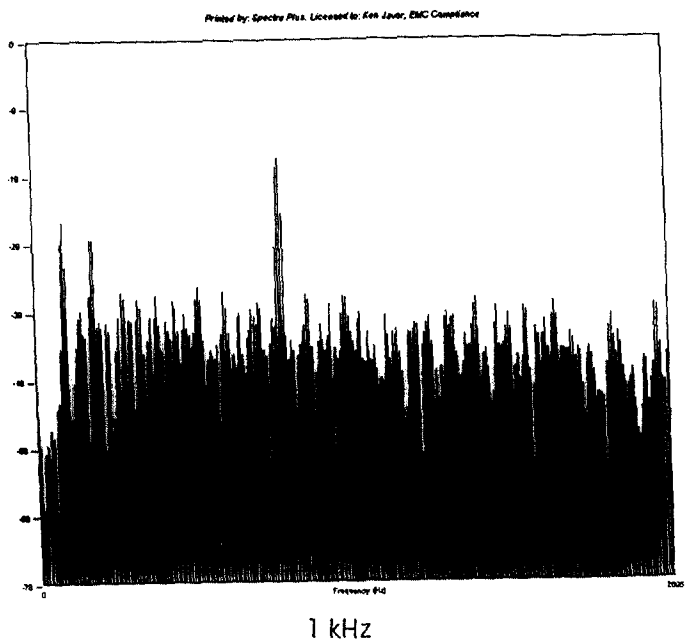

Figure 13: Radio audio output response to simulated broadcast signal

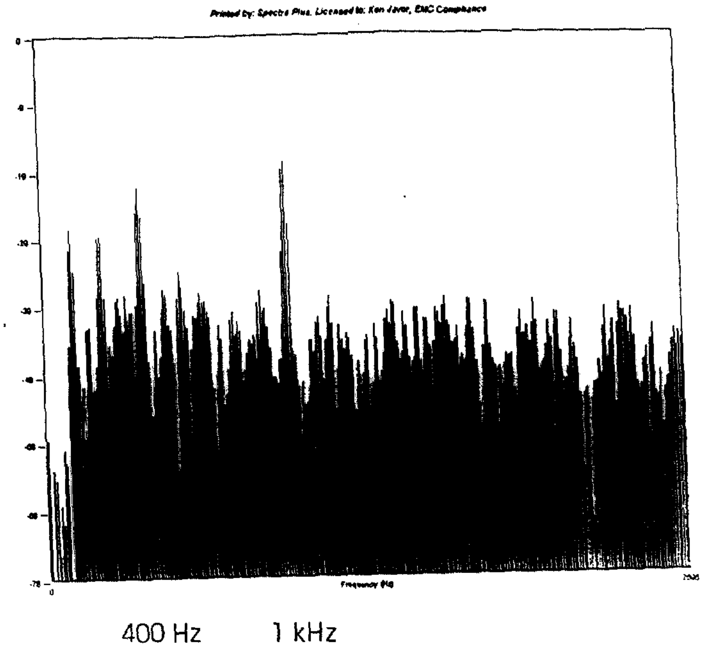

Figure 14: Fig. 13 radio audio output response with conducted rfi at TOI point

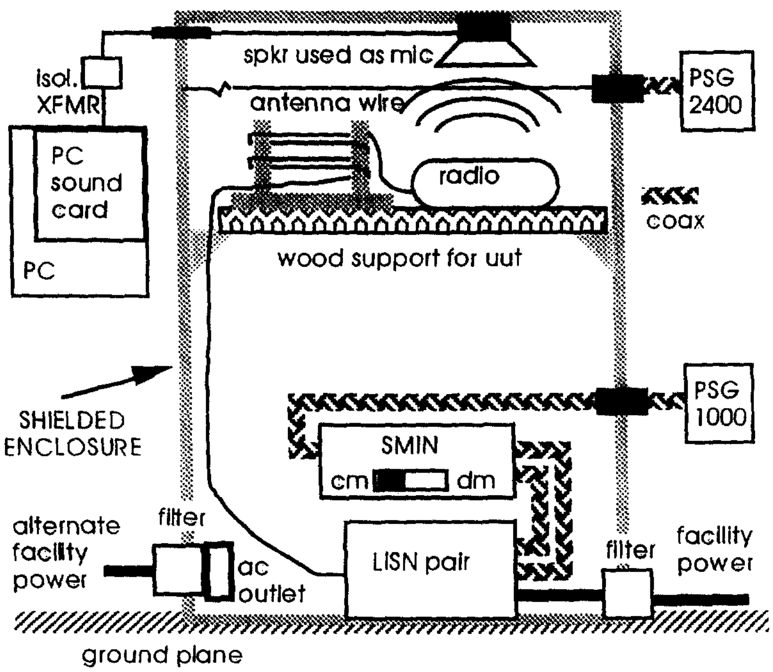

Figure 15: *Physical test set-up for measuring cm/dm TOI*

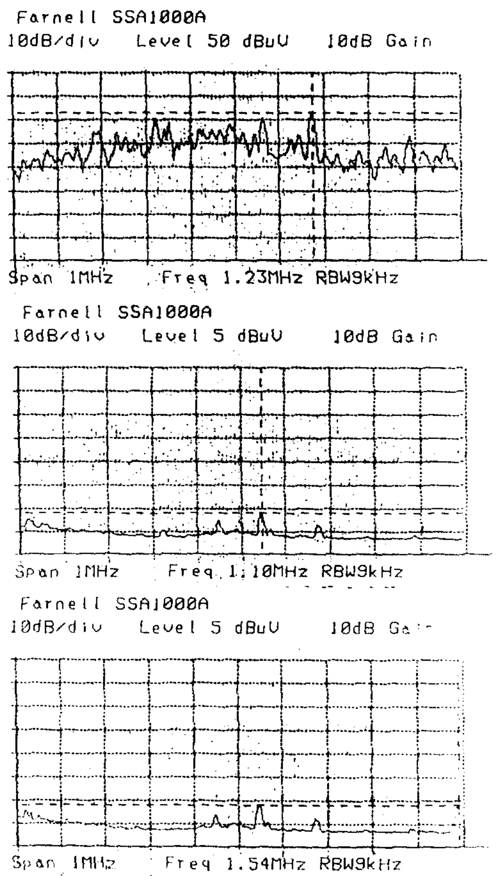

Figure 16 a,b,c: *Study rfi ambients*

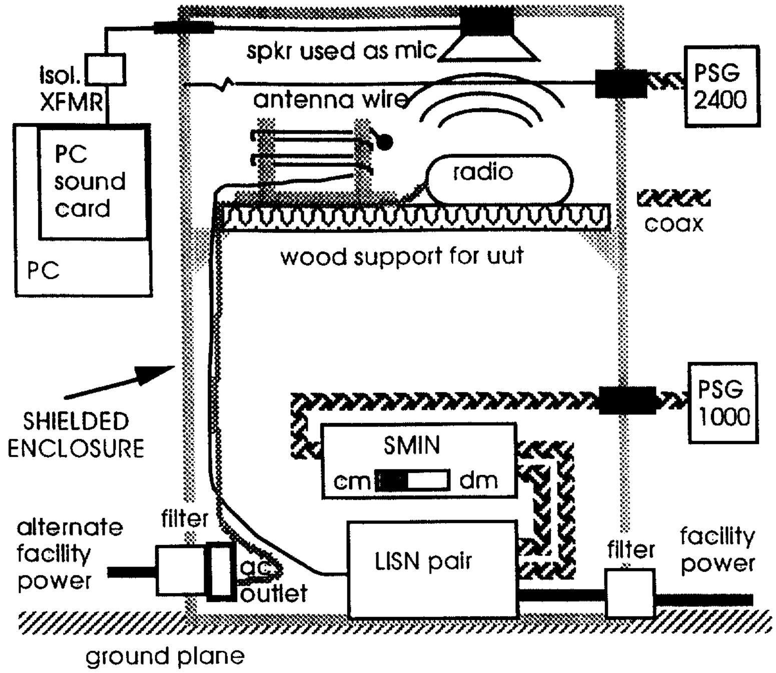

Figure 17: *Physical test set-up to assure dominance of conducted interference*

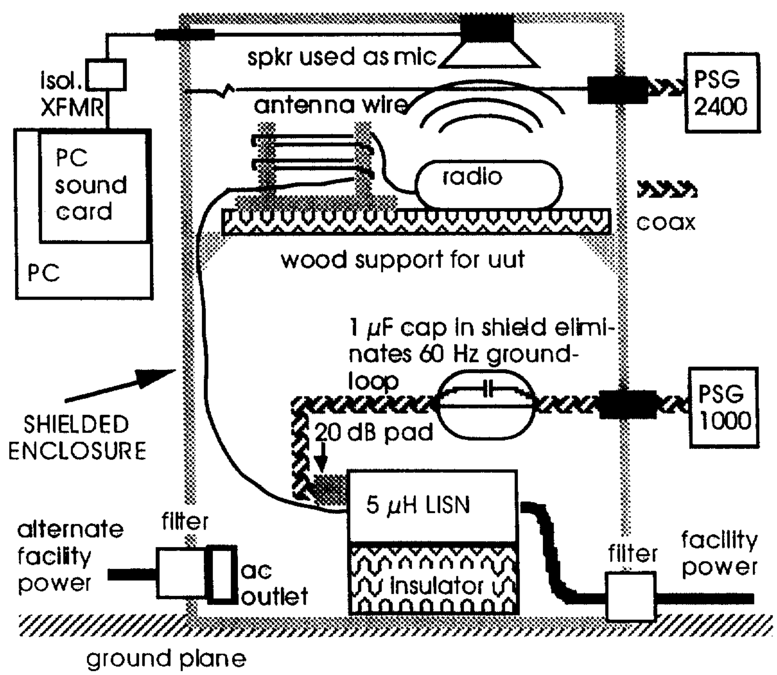

Figure 18: *Physical test set-up to measure radio TOI similar to CBEMA*

3.0 TEST RESULTS

A market survey finds roughly four categories of consumer oriented radio receivers. These are two band (AM/FM) receivers, alarm/clock radios, stereo (hi-fi) tuners, and multi-band radios (typically including some combination of short-wave/TV/weather in addition to the AM/FM bands). Each type of radio is represented in the study. Breakdown of radios (each one assigned an identifying number between 1 and 33) by type is shown below.

RADIO CLASS	RADIO INDENT NOS.	SPECIAL FEATURES	# RADIOS THIS CLASS
Clock/alarm	1,7 to 11,13,14,16, 21 to 24,28,31,33	33 has analog clock	16
AM/FM	4,5,15,26,27,29,30	all except 5 are portable; 5 is a '60s era Hi-Fi tube type	7
AM/FM/ cassette	3,6,32	3 is an expensive early "boom box", quite sensitive relative to others	3
Hi-Fi stereo tuner	17,18,19,20,25	18 is early '70s, most sensitive in this class @ -120 dBm	5
Multi-band & Shortwave	2,12	2 is only s/w receiver tested	2

All radios tested were bought from retail outlets. These included department stores, stereo (hi-fi) shops, and electronics outlets. One radio tested was a high quality 1960's vintage tube-based design. One stereo tuner was an early 1970's model sporting the qualifier "solid-state;" inspection of interior revealed not a single integrated circuit. It was by far the most sensitive receiver tested. Several tuners had sophisticated digital tuning (synthesized local oscillators) and controls. Many inexpensive clock radios appear to be nothing more than a user interface connected to a single IC. What all radios observed and tested had in common was two factors: a linear power supply and a two wire (phase and neutral, no green or safety wire) ac power input. These factors impact performance (vis a vis power line rf noise) as follows.

Linear power supplies draw 60 Hz and/or 120 Hz current waveform. Since ac power source impedance is very low, there is no need to provide local dm low impedance energy storage, as for an SMPS. Filtering consists of enough capacity on power supply secondary to prevent objectionable 60/120 Hz ripple from entering audio stage. This type of filtering can be performed with electrolytics, which are notoriously poor filters at radio frequencies. Inspection of many of tested radios revealed not a single case of rfi specific filtering.

Lack of a case ground obviates any attempt at line-to-ground filtering (filtering effective against cm CE). This single factor is the clue that radios might be expected to be more susceptible to cm than dm CE. Although dm filtering is only that residual level obtained fortuitously from ripple filters, it at least exists.

Above comments should not be interpreted as a condemnation of present practices. In particular. cm filtering would be problematical even with a case ground. Some radios utilize their power cord as an FM antenna rather than provide a collapsible rod or antenna port (typically small clock/alarm types). Effective filtering of AM band rfi while passing FM signals is not economical in such inexpensive devices.

3.1 Threshold of Interference Survey Results

Figure 19 graphically portrays raw TOI measurements for all radios tested. A fairly consistent differential is evident between cm and dm TOI. In general, cm TOI is slightly below CBEMA TOI. In and of itself, Figure 19 data supports study conclusion but is not overly instructive. A subtle normalization technique is enlightening. Consider that original CBEMA ESC5 testing likely resulted in a similar scatter plot, but a single limit of 48 dBμV was derived.[8] If in Figure 19 CBEMA test results are normalized to 48 dBμV, and normalization factor for each radio is then applied to both cm and dm TOI, Figure 20 emerges. Reduction in scatter evident in Figure 20 allows for mode unique limit setting by statistical methods. Figure 20 is rather busy; Figure 21 shows statistically derived means and standard deviations vs. FCC/CISPR limits as a function of frequency in the AM band.[9] Figure 21 demonstrates two most important conclusions. First, that dm CE limits can be easily set near 70 dBμV, a relaxation of 22/14 dB relative to FCC/CISPR Class B, respectively. Second, that not only is there better than 20 dB difference between mean cm and dm TOI, but there exists more than 10 dB difference between one standard deviation below the dm mean, and one standard deviation above the cm mean. Mode specific TOI differences are statistically significant.

3.1.1 Normalization Factor, Justification

Above analysis compares measured CBEMA TOI and uses individual differences from 48 dBμV to adjust cm and dm TOI. This raises questions of linearity of TOI with changes in broadcast/rfi level. Two types of testing were performed to measure such linearity and justify the normalization. First, Figure 22 shows variation in cm to dm TOI ratios (dB) vs. received broadcast level (and hence conducted rfi level). High degree of linearity over as much as a 50 dB change in levels is demonstrated. (Inspection of Figure 19 reveals that in every case, CBEMA TOI was less than 50 dB different from 48 dBμV. In fact, all but seven radios' CBEMA TOIs were between 28 dBμV and 60 dBμV). Second, four different radios had the extrapolation precisely tested, with excellent results. These are shown in Figure 23.

[8] Author's conjecture; CBEMA ESC5 report does not include such test data.

[9] One (European model) radio operating below 530 kHz was tested. Its cm/dm ΔTOI was comparable to other models tested; but most importantly, its long wave (LW) ΔTOI was consistent with its medium wave (MW) TOI. TOI measurements on a shortwave receiver at 11 MHz yielded similar results to AM band. Author expects results of this study to be valid for entire CE band of control, as long as AM receivers are protected victims.

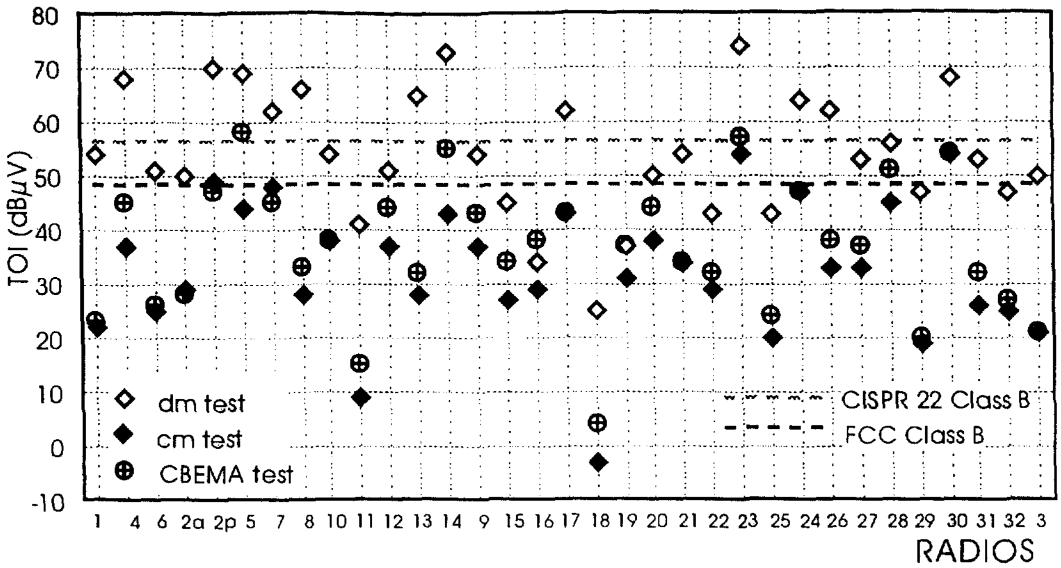

Figure 19: *TOI of AM radios with broadcast reception at 10 dB $\frac{S+N}{N}$*

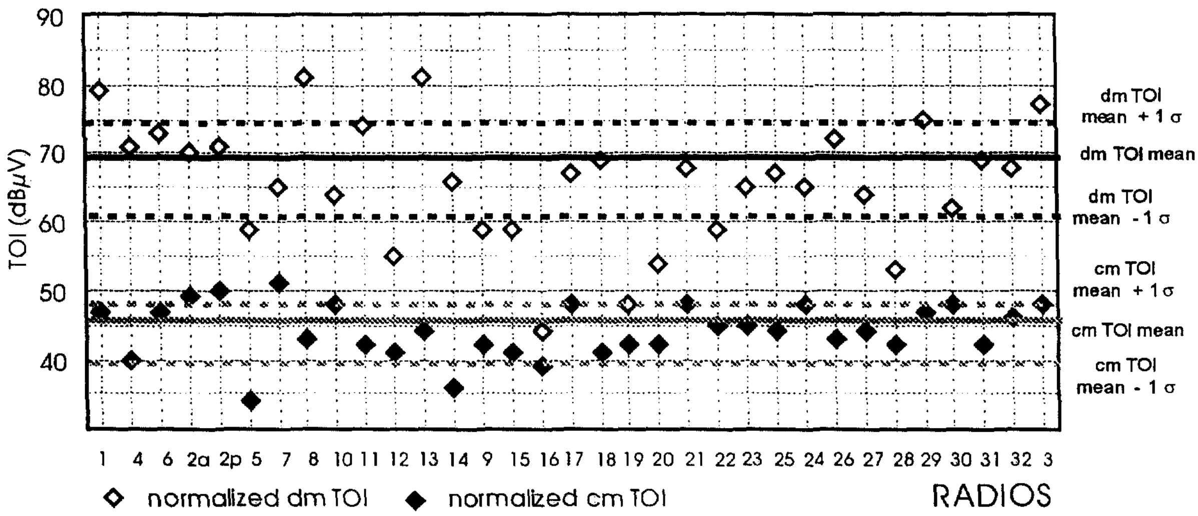

Figure 20: *Figure 19 with CBEMA TOI normalized to 48 dBµV*

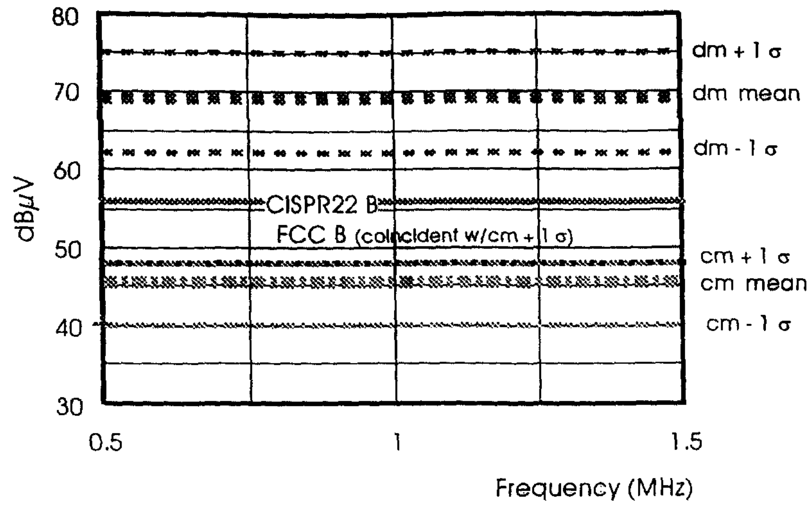

Figure 21: *Statistical means/standard deviations vs. commercial CE limits*

3.1.2 Effect of Tuned Frequency on TOI

Another factor requiring control as a source of error is any effect on TOI due to tuned frequency. Most radios tested in Figure 19 were tested at a mid-band frequency near 1 MHz. But not in all cases. In order to quantify the effect, if any, of tuned frequency on TOI, several radios had their (cm and dm) TOIs measured at three frequencies, low-, mid-, high-band. Results are shown in Figure 24. Effect of tuned frequency is seen to be random, and of insufficient magnitude to affect test validity or conclusion.

3.2 "Standardizing" DM TOI

Mean dm TOI in Figure 20 is 69 dBμV, which leaves several radios with lower actual dm TOIs. A simple way to increase (and "standardize," or reduce range of variation) dm TOI is to place a small capacitor across each radio's ac power input. A line voltage rated 0.047 μF capacitor was chosen for this function. Radios with good dm TOIs saw little or no improvement, but low dm TOI radios saw as much as 20 dB improvement. This is to be expected since an inherently high dm TOI is not as easy to improve upon as a poor performance.[10] Figure 25 illustrates that of radios thus modified, all but one achieved a dm TOI of 69 dBμV. One radio which failed to achieve a 69 dBμV dm TOI was an older radio with a unique design feature; there was a phase connection to one side of radio's loudspeaker. Notice that this radio's cm and dm TOI were coincident prior to X-capacitor addition. This was the only such case, and may have been due to complete bypassing of filtering effects of ac power supply.

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[10] Formal mathematical treatment: Nave 1991, discussion and proof of Sequential Element Theorem.

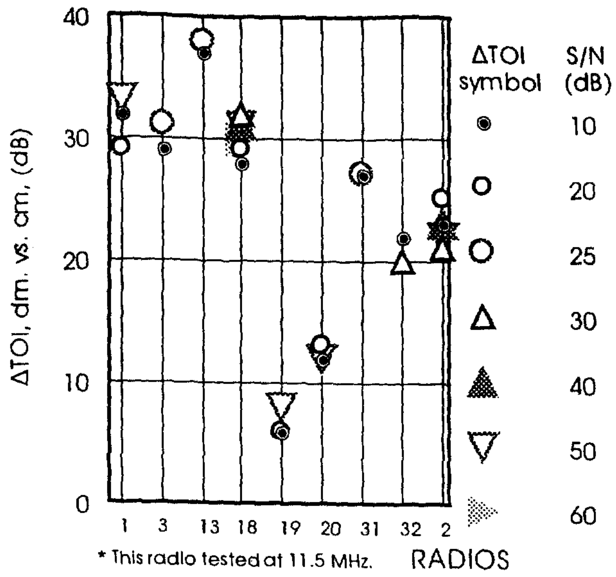

Figure 22: *CM/DM TOI ratio linearity vs. received signal strength*

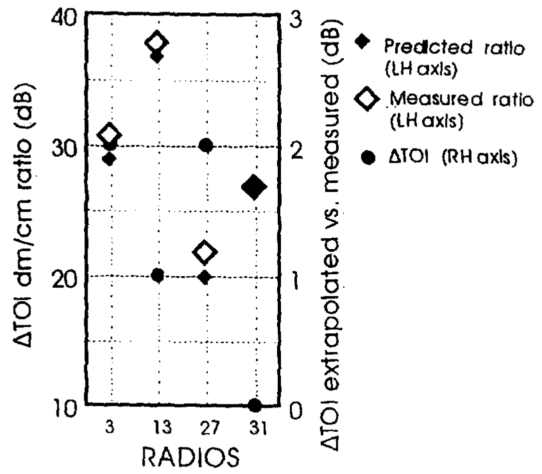

Figure 23: *Predicted vs. measured dm/cm ΔTOI*

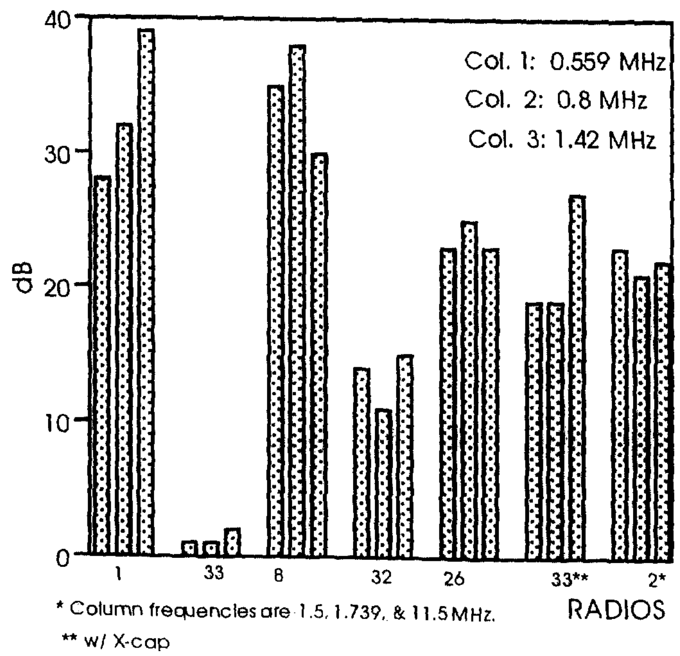

Figure 24: *TOI variation vs. radio tuned frequency*

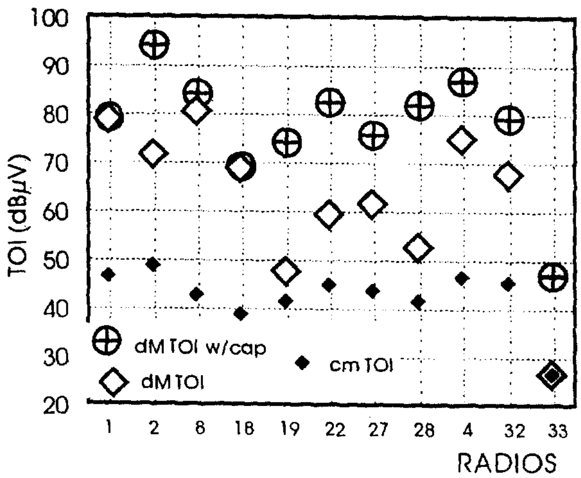

Figure 25: *Effect of adding 0.047 μF X-capacitor*

3.3 Mode Specific Susceptibility To Transient (Broadband) Noise

All previously described theory and test related specifically to narrowband (per test, actually cw) rfi. A question could be raised as to applicability of such theory and test to broadband phenomena. Although there is no obvious reason to expect different results, testing performed on two radios confirms that cm vs. dm delta TOIs are, if anything, larger than that measured using a cw rfi source. Radios 21 and 29 were subjected to BB conducted rfi. Radio 21's BB dm/cm susceptibility threshold ratio was more than 23 dB higher than its cw ratio, while radio 29's BB dm/cm ratio was 6 dB higher than its cw ratio.

3.3.1 Broadband Source

A broadband source was created using a 5 ns risetime, 50 Ω output pulse generator set to produce a 2 μs pulse width with 400 Hz repetition rate. A 4700 pF capacitor was added in series with pulse generator output to attenuate low frequency components; increasing spectrum analyzer dynamic range when measuring this extremely broadband signal. Figure 26 shows pulse waveform and period at level which caused cm TOI to one radio. This repetition rate, relative to a 9 kHz measurement bandwidth, or a 6 kHz bandwidth AM radio yields a broadband response. Figure 27 is frequency domain representation of same signal shown in Figures 26. Figure 27 is taken with spectrum analyzer in peak hold mode over several sweeps. Top trace is peak detector output, while lower trace utilizes video averaging for a pseudo-averaging effect. Broadband nature is evident in this figure.[11]

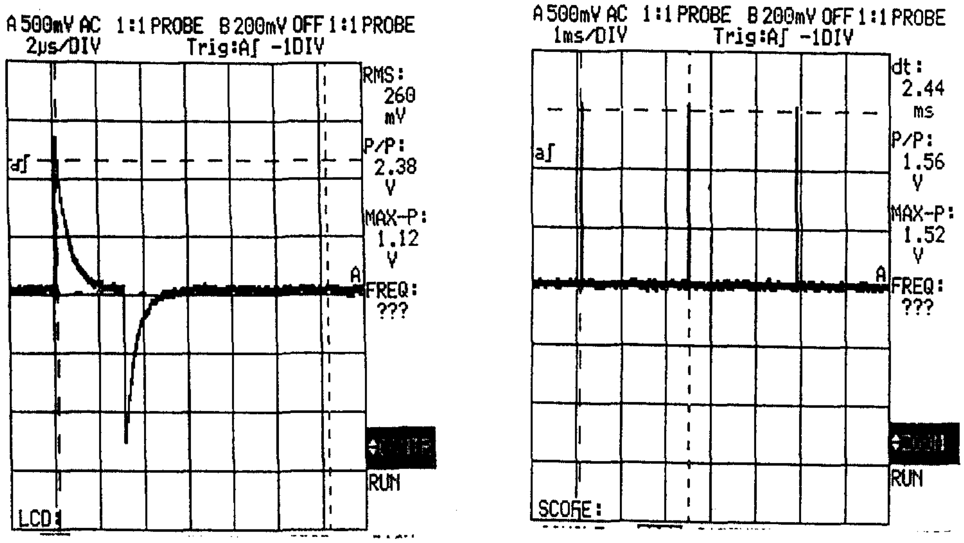

Figure 26: *Broadband pulse time domain waveform*

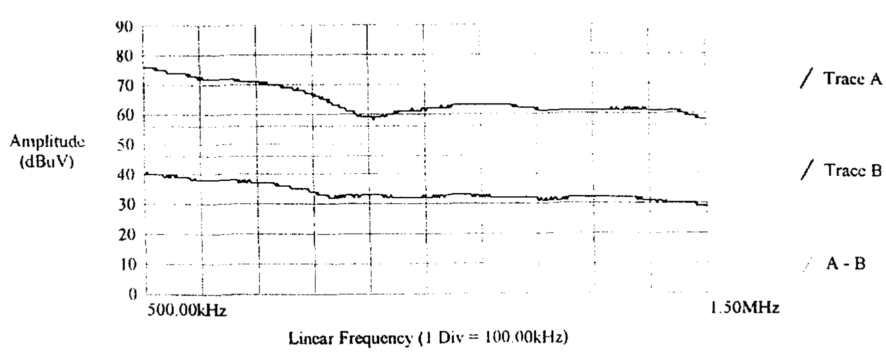

Figure 27: *Broadband pulse AM band spectrum*

[11] Due to hardware and software set-up, upper trace numerical values are 46 dB above level actually applied to LISN connected power conductors.